Capture and Sequestration of Greenhouse Gases in Canada

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ABSTRACT

The capture and geological sequestration or storage of CO_2 represent an attractive option for Canada to reduce its greenhouse gas emissions. Modelling studies indicate that this technology could account for 20% of the emission reductions required to bridge the gap between Canada's Kyoto target and the predicted business-as-usual emissions. This paper will review the status of CO_2 capture and storage technology in Canada. Following an overview of the country's greenhouse emissions, its reduction targets and its large potential geological storage capacity, past and present capture and storage activities will be reviewed, the technology described and process economics summarized. Current capture and storage projects and initiatives, ranging from modest laboratory studies to field pilots are then highlighted.

1. INTRODUCTION

Action Required to Reduce World Greenhouse Gas Emissions

Scientific evidence now strongly suggests that increasing anthropogenic (human-induced) emissions of greenhouse gases (GHG), principally carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), may lead to higher temperatures and cause climate changes on a global scale (Figure 1). It is also recognized that the world-wide production, transportation, combustion and/or use of fossil fuels is the major source of anthropogenic GHG emissions (about 85%).

The issue of global climate change due to the release of these greenhouse gases has become one of the most important and challenging environmental issues facing the world community. While the magnitude of the changes and their possible impacts are still very uncertain, the world has accepted that limits have to be placed on anthropogenic GHG emissions. In Rio de Janeiro in 1992, 154 countries signed the Framework Convention on Climate Change (FCCC). It is the FCCC's ultimate objective to stabilize GHG concentrations in the atmosphere at a level, which would prevent dangerous anthropogenic interference with the global climate system.

Although there is no agreement what the appropriate level would be, a level of 550 ppm – twice the pre-industrial level of 280 ppm - is often used as reference for emission reduction planning. Stabilization at 550 ppm would lead to an equilibrium temperature increase of about 1.5ºC. In order to achieve even this modest stabilization level, very significant emission reductions of well over 50% below today's levels would be required (Figure 2). As a first step, developed countries, through the Kyoto Protocol of December 1997, agreed to reduce their emissions by an average 5.2% below 1990 levels over the period 2008-2012.

Canada's Climate Change Initiatives

Canada signed the Kyoto Protocol and committed the country to work toward the ratification of a binding target. The target is to reduce annual GHG emissions to a level of minus 6% by the 2008-2012 time frame relative to the 1990 level, which is estimated to have been the equivalent of 601 megatonnes (Mt) of CO_2.[1]

In early 1998, the Canadian federal, provincial and territorial ministers of energy and the environment initiated work on a national climate change strategy with a mandate to develop a plan to meet the Kyoto target. Sixteen "*Issue Tables*" or consultative working groups, with approximately 450 experts from government, industry, academia and non-governmental organizations, each investigated a specific economic sector or cross-cutting policy area. The mandate of the Tables included the tasks of examining the impacts, costs and benefits of addressing the climate change issue and developing "options" for GHG mitigation policy, with an indication of the level of support for these options among the Table members. By spring of 2000, all of the Tables had prepared extensive final reports, containing well over 100 options in total. Together, this rich resource of information represents the most comprehensive study of GHG sources and reduction potentials ever undertaken in Canada.

Three of these Tables, covering the areas of technology development, the electricity generation industry and the upstream oil and gas industry (a subsector of the Industry Table), independently arrived at the conclusion that capture of CO_2 from large emission point sources, typically fossil fuel-fired systems, and subsequent geological sequestration would contribute significantly to reducing Canada's GHG emissions.[2]

Based on these options and further stakeholder meetings, a *National Implementation Strategy on Climate Change* has been developed and accepted by Ministers in October 2000. This strategy will be implemented through a series of three *Annual National Business Plans*, the first one of which will start in 2001. The Implementation Strategy recognizes the significant contribution the capture and storage option can make to CO_2 emissions mitigation and recommends further consideration. The First Business Plan takes the recommendations one step further and proposes concrete action items on capture and storage.

Private sector interests are also emerging: carbon dioxide capture from coal-fired power plants is a centre-piece of a 10-year, $1 billion R,D&D plan proposed by the recently-formed Canadian Clean Power Coalition, an alliance of western Canadian coal-based electric utilities and coal producers.

Canada is not alone in recognizing the potential of this mitigation option. Some activities in other countries will be referenced later in this paper. In several aspects of the development of this option, however, Canada is playing an international leadership role, including chairing the Executive Committee of the International Energy Agency (IEA) Greenhouse Gas R&D Programme. There are also several high-profile Canadian projects, which are supported by both domestic and offshore partners; they will be summarized later in the paper.

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[1] Greenhouse gases have different warming potentials. In order to make comparisons possible, all emissions are converted to equivalent CO_2 emissions.

[2] The term 'geological sequestration' is generally used interchangeably with 'storage' or 'disposal', and is different from 'sequestration in terrestrial ecosystems'. In Canada, 'storage' is the preferred term.

Canada's Greenhouse Gas Emissions Profile

In order to understand the climate change challenge Canada faces and appreciate possible GHG mitigation options, a brief examination of the nature of Canada's GHG emissions is in order. Canada's total GHG emissions in 1997 were 682 Mt (approximately 2% of total global emissions). Of the six greenhouse gases covered by the Kyoto Protocol, CO_2 was the greatest contributor to Canada's total GHG emissions in 1997, representing 76% (or 520 Mt) of total emissions. Methane was the second largest contributor with 13%, while nitrous oxide (N_2O) emissions represented 9% of the Canadian total.

GHG emissions in Canada are primarily related to the production, transmission and use of fossil energy, and are deeply embedded in the country's economic and social structure. Due to Canada's vast geography, the relatively harsh climate, a relatively high population growth rate and the high energy requirements of Canada's resources industry, energy demand per capita in Canada is higher than in almost all other countries. These fossil energy-related emissions accounted for approximately 80% of total emissions in 1997. They comprise fossil fuel combustion activities, including electricity generation, energy-related industrial processes, and transport. The combustion of fossil fuels alone was responsible for approximately 66% of all GHG emissions: 41% was generated in stationary sources (electricity generation, industrial, commercial, institutional or residential) and 25% in mobile sources (transportation). The GHG emissions from fossil fuel combustion consisted primarily (96%) of CO_2.

Electricity generation from all fossil fuels combined accounted for 16% of total GHG emissions or 21% of total CO_2 emissions. The use of coal for electricity generation contributed 81% of all emissions from electricity generation, or over 17% of total CO_2 emissions. If other uses of coal are included (i.e., steelmaking and industrial combustion) coal accounted for about 21% of total CO_2 emissions, or 16% of Canada's total GHG emissions.

Projected Greenhouse Gas Emissions in Canada

According to the latest BAU (Business-As-Usual) projections by Natural Resources Canada, incorporating existing energy efficiency policies, total GHG emissions are estimated to increase to 764 Mt or 27% above 1990 levels by the year 2010. By the year 2020, if no further mitigative policies or actions are taken, emissions are expected to rise 41% above 1990 levels. The Kyoto Protocol's emissions limit for Canada is 565 Mt for the period 2008-2012. To achieve this target, emissions need to be reduced by 199 Mt. This represents a gap of some 26% between the forecast projection and the Kyoto target (Figure 3). While this gap is significant, the forecast projection is lower than it would have been in the absence of past and current initiatives. Without the existing National Action Plan on Climate Change, which was initiated in 1995, Canada's GHG emissions in 2010 would have been about 8% higher than the above BAU forecast, and the Kyoto "gap" would have been about 30% higher.

According to these projections, the most significant contributors to emissions growth between 1990 and 2010 will be the fossil fuel production industry (oil sands), which is projected to increase its emissions by 64%, and the transportation sector with a 34% projected growth. Electricity sector emissions are projected to grow quickly until 2015 (over 25%), and then decline sharply as coal-fired plants are retired and replaced by natural gas or more efficient coal plants.

GHG emissions, on a tonnage basis, vary widely across the country and their growth rates also differ markedly. The largest emitter is Alberta, closely followed by Ontario. Emissions are expected to grow most quickly in Alberta and Saskatchewan due to continued or accelerated oil, gas and oil sands production.

2. THE CO_2 CAPTURE AND STORAGE OPTION FOR CANADA

A Significant Opportunity For Canada

Basic options for reducing GHG emissions typically include (1) increasing the efficiency of energy production and reducing energy consumption (end use) and (2) switching to lower or zero carbon fuels (nuclear, renewables) and reducing GHG's from non-energy sources. A third option - reducing the net emissions of CO_2 by sequestering the gas either through enhanced biological sinks or by capturing it from large point sources and storing it underground in geological formations, deep oceans or as a solid carbonate - is a relatively new concept that only recently has started to draw worldwide attention. Carbon dioxide capture and storage will permit the production of CO_2 but prevents its emission. It is an attractive option because it would allow Canada the continued use of its immense and cheap fossil fuel reserves without the associated negative climate change impact, while providing the time required for the transition to lower carbon intensive technologies.

The CO_2 capture and storage option is particularly applicable in the western Canadian provinces of Alberta and Saskatchewan, where large fossil-fuel users are a major source of CO_2 emissions and where suitable geological reservoirs are available as storage sites close to point source emitters. Emissions associated with oil and gas production, processing and transportation to markets are also significant in these provinces. Electric power generation is also the largest point source of emissions in the eastern provinces of New Brunswick and Nova Scotia and, again, there is access to geological reservoirs for CO_2 storage, including deep coal seams and aquifers. In Ontario, aquifers may also exist to store CO_2 captured from fossil-fired electricity generation plants in that province, but the suitability and extent of these aquifers are still largely unknown. Other provinces, including British Columbia, Manitoba and Québec, make extensive use of hydro-electricity and, therefore, have low emissions of CO_2. Figure 4 shows where in Canada the main geological storage reservoirs are found and where major GHG sources are located.

It is estimated that of the approximately 600 Mt of CO_2 that will be emitted in 2010 in Canada, about one-quarter will come from large point sources, although not all of this will be within an acceptable economic distance of a geological storage site. Therefore, the quantity of CO_2 available for storage is estimated to be 100 Mt per year. The lion's share of this, about 75 Mt, will come from Alberta, where more than half of all emissions come from major point sources, including coal-fired power stations, oil sands plants and refineries.

The existing (rough) estimates of Canadian geological CO_2 storage capacities are very much greater than the CO_2 available for capture. Estimates are preliminary and fragmented at present, and are available only for Canada's western sedimentary basin. The storage capacities in the Alberta portion of that basin, are:

aquifers	10^5 -10^6 Mt CO_2
coalbed methane	10^4 -10^5 Mt CO_2
depleted natural gas reservoirs	10^3 -10^4 Mt CO_2
enhanced oil recovery	10^2 -10^3 Mt CO_2

The capacity of geological sites in Alberta thus provide, in theory, storage for all of Alberta's emissions for the foreseeable future. Storage capacities available in other provinces are not as well documented, although the Geological Survey of Canada is leading a modest program to characterize the storage potential of coalbed methane reservoirs across Canada, especially specific sites in the vicinity of major CO_2 point sources located in sedimentary basins.

Capture and storage could significantly contribute to Canada's required GHG reductions and limit the overall costs of the country's GHG mitigation strategy. Recent modeling studies indicate that close to 10 Mt per year of CO_2 could be stored in oil reservoirs (EOR) in the Western Canadian Sedimentary Basin at a net cost of C$13 per tonne. A further 30-40 Mt per year could be stored in deep coal seams or aquifers at costs of up to C$38 per tonne. These estimates led to the important conclusion that, if deployed widely and in a timely fashion, CO_2 capture and storage could ultimately account for a significant proportion of Canada's GHG mitigation needs, conceivably up to 20% of the approximately 200 Mt reduction which would be required by the year 2010. Although it is improbable that capital projects will actually be in place to capture and store 30-40 Mt CO_2 per year a decade from now, this does emphasize that this option has finally come of age in Canadian planning.

History Of CO_2 Capture And Storage In Canada

There has been interest in Canada in various aspects of CO_2 capture and storage technologies for the past 20 years. Early work was done in enhanced oil recovery (EOR) by CO_2 injection, CO_2 capture, and CO_2 removal through O_2/CO_2 combustion. The following is a list of the main highlights:

1980-82	Operation of CO_2 capture pilot facility at Sundance power station, Alberta
1980+	CO_2 enhanced oil recovery (EOR) projects initiated in Alberta and Saskatchewan
1986	Operation of CO_2 capture pilot plant at Boundary Dam, Saskatchewan
1991	Start of studies on improved amine solvents and column packing materials for CO_2 scrubbing at the University of Regina
1992-93	Large multiclient study on CO_2 capture and disposal in Alberta
1992-94	Study of CO_2 disposal in deep aquifers in Alberta
1994	Construction of an O_2/CO_2 combustion pilot plant at federal laboratories, Ottawa
1997	Start of a CO_2 coal bed methane field test at Fenn-Big Valley, Alberta
1999	Participation in a CO_2 monitoring project at PanCanadian's EOR project, Weyburn, Saskatchewan
1999	International CO_2 Capture Test Centre initiated at the University of Regina
1999	Participation in the Zero Emission Coal Alliance (ZECA) by Canadian utilities, coal companies, and the federal and Alberta governments.

The National Initiative on CO_2 Capture and Storage

Last year, over 80 managers and scientists from Canadian industry, governments, academia, non-governmental organizations and from outside Canada have formed a voluntary network to stimulate and organize the development and deployment of technologies for the large-scale implementation of capture and storage of CO_2. Known as the *National Initiative on CO_2 Capture and Storage*, it is a window into events on CO_2 capture and storage in Canada and abroad, a means of expanding contacts and collaboration, a tool for setting corporate research priorities and stimulating collaborative projects, and it is available to influence government policies. It does not have funding capability nor is it designed to be directive on commitment to projects.

There are three working groups. A CO_2 capture group targets areas of interest that include absorption, O_2/CO_2 combustion, and membrane and cryogenic separation. A geological storage group includes enhanced oil recovery (EOR), coalbed methane (CBM), deep saline aquifers, and an inventory of storage sites. A technology deployment group discusses the regulatory, royalty and tax infrastructure, which could have a bearing on deployment. A national steering committee organizes the process, but not the content, of the Initiative.

During 1998-1999, a series of workshops was held by the National Initiative in western and eastern Canada. The outcome of these workshops was (1) a preliminary master plan, which identified candidate technologies for capture, transportation, and geological use and storage of CO_2, as well as research needed to advance these technologies (see Appendix for details); (2) an assessment of the barriers and issues facing practical deployment of these CO_2 capture and storage technologies in Canada; and (3) identification of what additional work needs to be done to better address deployment related concerns.

Further consultations are required to confirm science and technology priorities and to finalize a national R,D&D program designed to lead to large-scale technology demonstration projects and first commercial plants. The plan then needs to be implemented through partnerships between the private sector, the federal government, the provinces and academia.

3. CO_2 CAPTURE AND STORAGE TECHNOLOGY

CO_2 Separation

CO_2 capture and storage firstly involves the separation of CO_2 from (a) fossil-fuel fired power plant or heating plant flue gases; (b) the effluents of industrial processes such as petrochemicals (ethane purification and ethylene production) and cement manufacture; and (c) the decarbonization of methane (reaction of natural gas with steam to produce hydrogen). Separation from these point sources can be accomplished by absorption after contact with amine-based solvents (the most common method), adsorption on activated carbon or other materials, by passing the gas stream through special membranes, or by cryogenic separation. However, costs are high and significant technical problems remain unsolved.

As well as separation from stack gases after fossil fuels have been combusted in the boilers of electricity generating stations, it is also possible to remove the CO_2 prior to combustion (pre-combustion decarbonization), for example by gasifying the coal using an integrated gasification combined-cycle (IGCC) system, or by burning the fuel in oxygen and concentrating the resulting CO_2 through recycling (this technique is known as O_2/CO_2 combustion).

Numerous engineering studies have looked at the cost of CO_2 separation in a variety of settings. Canadian estimates indicate that CO_2 could be produced at the plant gate for about

C$35 per tonne, but costs as low as C$25-27 per tonne may be possible. The goal for a national program would be to refine existing technologies by improving capture process integration and reducing capital requirements, so that the cost would be reduced to about C$20 per tonne CO_2.

Transportation

Secondly, CO_2 capture and storage involves the transportation of the separated CO_2 to the use or storage site. CO_2 pipelines are already in operation in the USA to transport the gas, often from natural CO_2 reservoirs, to oil fields where it is used to enhance oil production. A 325-km pipeline has just come on stream, delivering 5000 tonnes per day of CO_2 from a coal gasification plant in North Dakota to PanCanadian's CO_2-based enhanced oil recovery (EOR) project at Weyburn, Saskatchewan. Transportation costs add in the neighbourhood of C$1.00 per 100 km per tonne.

Use and Storage

Thirdly, CO_2 capture and storage involves the use of the CO_2 as a solvent in oil field reservoirs or its sequestration in underground reservoirs or the oceans (Figure 5). Because of the high potential for geological storage in Canada, specifically in the Western Canada Sedimentary Basin, this option is the main focus of this paper.

There are three types of geological formations in western Canada that could be used for storing CO_2:

- active and uneconomical or depleted oil and gas reservoirs
- deep and unmineable coal seams, and
- deep saline aquifers.

Use in Enhanced Oil Recovery and Deep Coal Seams

Considerable economic benefits can accrue when CO_2 is used in producing oil fields as a miscible or immiscible solvent for enhanced recovery. Under these circumstances, CO_2 is a commodity that commands a price, which will offset the costs of capture and transportation. The main factors influencing the price an oil field operator can afford to pay for CO_2 will the type of oil reservoir and the price of the incremental oil produced. This 'affordable' CO_2 price could be as high as C$30 per tonne for the better Canadian reservoirs (based on an oil price of US$20 per barrel). If the current high prices of oil and gas are sustained and the combined cost of capture and transportation come down to the C$30 per tonne level, there will be an economic incentive to start considering capturing CO_2 from power plant flue gases. The same situation would also apply to supplying CO_2 to projects for enhanced coal-bed methane recovery, enhanced gas recovery, enhanced in-situ bitumen recovery, and the in-situ upgrading of bitumen and heavy oils.

About 70 oil fields worldwide use injected CO_2 for enhanced oil recovery, including the Weyburn field in Saskatchewan. The purity of the CO_2 required can affect capture costs. It may be possible to reduce capture costs by injecting CO_2 mixed with other gases, for example flue gases containing sulphur and nitrogen oxides, but reservoir reactions to such mixtures would need to be studied.

Canada is leading an international effort to evaluate the displacement of methane from coal seams with CO_2, the methane then being produced as a fuel for heating or electricity generation. Since at least two volumes of CO_2 are sequestered for each volume of methane produced and the adsorption is largely irreversible, this storage option is considered promising in terms of the economics of electricity generation.

Storage in Aquifers and Oceans

CO_2 sequestration in a sub-seabed saline aquifer is already being practised in the North Sea off Norway (the Sleipner Project). Results from a Canadian three-year study on the aquifer disposal of CO_2 were published in 1996. This study, done by the Alberta Research Council on aquifers in the Western Canada Sedimentary Basin, demonstrated that both hydrodynamic trapping (no reaction between CO_2 and formation water and aquifer minerals) and mineral trapping (reactions occur and minerals are precipitated or dissolved) are viable processes for the storing of CO_2 in the subsurface, depending upon the reservoir properties. The study indicated that very large volumes of CO_2 could be stored for hundreds to thousands of years.

Canada is also participating in an international consortium studying the environmental aspects of the injection and storage of liquid CO_2 in the ocean off Hawaii. It is estimated that storage in depleted oil and gas reservoirs, deep saline aquifers and deep oceans would add approximately another C$2.00 per tonne.

Conversion and Storage of CO_2 as a Solid Mineral

Finally, Canada, as a participant in the *Zero Emission Coal Alliance* (ZECA), is investigating a zero-emission coal concept, part of which involves the conversion and permanent storage of CO_2 as a solid carbonate mineral (more details follow below).

4. CURRENT CO_2 CAPTURE AND STORAGE ACTIVITIES IN CANADA

There are several projects underway in Canada which are making significant contributions to the knowledge and practical application of CO_2 capture and storage. These projects encompass reduction of CO_2 capture costs, monitoring of CO_2 behaviour after injection into an oil field, enhanced recovery from an abandoned oil field using CO_2 injection, increasing CO_2 concentrations in flue gases using O_2/CO_2 combustion, injection of CO_2 into deep coal beds to enhance methane recovery, assessing the CO_2 storage capacity of Canadian sedimentary basins and coal seams, and gasifying coal to produce a stream of pure CO_2 for conversion into a solid carbonate.

International Test Centre for CO_2 Capture

The International Test Centre in Saskatchewan, announced in 1999, has two main components: a pre-commercial-scale chemical absorption technology demonstration pilot plant at the Boundary Dam power plant near Estevan, and a technology development pilot plant at the Petroleum Technology Research Centre of the University of Regina. It will examine refinements to current technology and ways of reducing the costs of capturing CO_2 from stack gases emitted from fossil fuel-fired electricity generating stations.

The original Boundary Dam pilot plant was built in 1987 at a cost of C$2.5 million under the sponsorship of SaskOil, Amoco Canada, Shell Canada, and the governments of Canada and Saskatchewan. An earlier absorption separation plant had been operated in Alberta for about 18 months in the early 1980's at the Sundance power plant. However, the cost of separation of the CO_2 for use in enhanced oil recovery projects was found to be prohibitively high and solvent degradation was a severe operating problem.

The technology demonstration pilot plant at the Boundary Dam power station, which will be an updated and refurbished version of the 1987 unit, is to be used for the improvement of the already commercial chemical absorption process using a variety of solvents. The smaller technology demonstration pilot plant at the university will be used for both the development of new technology and technology screening.

Funders include the governments of Canada, Saskatchewan and Alberta. Industry partners committed to the project include Fluor Daniel, Luscar, SaskPower, EPCOR, TransAlta Utility Corp., BP Amoco, Canadian Occidental and PanCanadian Petroleum.

IEA CO_2 Monitoring Project at Weyburn, Saskatchewan

This project builds upon the $1.1 billion PanCanadian Weyburn CO_2 EOR project in which CO_2, pipelined from the Dakota (coal) Gasification Company in Beulah, North Dakota, will be pumped into the Weyburn field to reduce the viscosity of the oil and thereby increase its recoverability. An incremental 120 million barrels of oil will be recovered over the next 15 to 20 years, at the same time storing about 14 million tonnes net of CO_2 underground (about 60% of the total injected).

The IEA (International Energy Agency) CO_2 Monitoring Project is focussed on assessing the long-term integrity of CO_2 storage when used for enhanced oil recovery at Weyburn. This four-year research program, which is starting with a pre-injection reservoir baseline study, will develop a comprehensive understanding of the storage integrity, migration and fate of CO_2 injected into an oil-bearing geological structure.

Total project cost will be C$35 million over the four years. Partners to date include PanCanadian Resources, the Petroleum Technology Research Centre and the Governments of Canada and Saskatchewan. SaskPower, BP Amoco, Dakota Gasification Company and TransAlta have indicated their intention to participate in the project. The European Union has also committed approximately $1.6 million to the project with more anticipated from other European sources.

This project will include researchers from Canada, the United States and Europe under the auspices of the *IEA Greenhouse Gas R&D Programme*. This IEA activity, chaired by Canada and with offices in the U.K., brings together the interests of 16 countries and the Commission of European Communities. Also, BP Amoco, DMT-FP, EPRI (Electric Power Research Institute, California), Mobil Oil, RWE AG and Shell International are sponsors.

Membership also provides access to information from other international projects, for example the Sleipner CO_2 capture and storage project of Statoil, the Norwegian state oil company. This project removes CO_2 from natural gas in the North Sea using an amine absorption process. The CO_2 is then compressed and injected into an aquifer 1000 m below the seabed. The Sleipner project is the largest CO_2 capture and storage project in the world, sequestering about a million tonnes of CO_2 per year.

O_2/CO_2 Combustion Technology

This project is being conducted at the pilot-plant facilities of the CANMET Energy Technology Centre at Bells Corners, close to Ottawa. The CANMET consortium includes five Canadian utility companies (TransAlta, EPCOR, SaskPower, Ontario Power Generation and Nova Scotia Power), two industry companies (Air Liquide Canada and the McDermott Corp.), the governments of Canada and Alberta, and the U.S. Department of Energy.

The principle of O_2/CO_2 combustion of fossil fuels is that the CO_2 concentration in the flue gases can be increased to greater than 95% by displacing air with oxygen in the combustion process, thereby minimizing the complexity of CO_2 capture from these gases. Nitrogen is separated from the combustion air and the CO_2 combustion product is recirculated through the combustor with the oxygen. The use of CO_2 recycle allows for proper control of boiler performance in retrofit situations. This technique also shows promise for the clean-up of other emissions such as nitrogen oxides, sulphur dioxide and particulates.

This project is now in its 5th phase. Pilot-scale O_2/CO_2 combustion trials are continuing and the techniques learned will be applied to a commercial burner design. As well as the opportunity to retrofit this technology to existing fossil-fired power plants, the possibility for a field demonstration project in conjunction with the coal-bed methane project, described below, has been discussed. In this application, O_2/CO_2 combustion would provide a CO_2-rich flue-gas stream that would be sequestered in deep unmineable coal beds while simultaneously recovering the methane trapped in the coal. The economic value of the methane recovered would offset the cost of storing the CO_2.

As part of this project, “virtual plant” models have been developed to simulate the effect of various CO_2 capture technologies on overall plant performance and to optimize overall system integration to reduce energy losses.

CO_2 Enhanced Recovery of Coal Bed Methane

The objectives of this project are to reduce GHG emissions by injecting CO_2 into deep coal beds and to enhance coal bed methane recovery and production rates as a result of CO_2 injection. This project is an Environment Canada-led initiative, with expertise from the Alberta Research Council. It is sponsored by the governments of Alberta, Canada, the U.S., the U.K., Australia and the Netherlands, as well as a group of more than 15 oil producers, utility companies and other interests. A single-well pilot was successfully tested in Fenn-Big Valley, Alberta, in 1999/2000, and a two-well pilot injection test is in the design stage for implementation in 2001.

CO_2 Storage Capacity Of Canadian Coal Seams

This modestly-funded project (federal government only) is being carried out from the Calgary office of the Geological Survey of Canada and seeks to understand the adsorptive capacity for CO_2 of representative coal samples from coal seams in Canada using laboratory isotherm experiments. Detailed studies on the areas in Canada with the highest potential for storage, including the east coast, are required but current funding is inadequate for this.

Canadian Clean Coal Power Coalition

This activity is still at the proposal stage. Leading Canadian coal producers and utilities have recently formed an association, known as the *Canadian Clean Coal Power Coalition*. The Coalition, currently comprising TransAlta, EPCOR, Luscar, SaskPower and the Alberta Research Council, has proposed a program with the aim of "securing a future for coal-fired electricity generation". The proposal includes:

- construction and operation of a full-scale demonstration project for the removal of greenhouse gas and all other emissions of concern from an existing coal-fired power plant by 2007,
- development of low-emission technology for new power plants, and
- an integrated air-quality covenant that tackles the entire portfolio of air quality issues related to coal-fired power generation.

Overall costs over the next 10 years for the full-scale demonstration project and demonstration of low-emission technology for new power plants are estimated to be nearly $1 billion. As an initial step, the Canadian Clean Coal Power Coalition has asked the governments of Canada, Alberta, Saskatchewan and Ontario to make a commitment of C$7 million in 2001 for the evaluation of technology options for both retrofit and new plant technologies. Coalition members would contribute C$1 million.

5. INTERNATIONAL JOINT CO_2 CAPTURE AND STORAGE ACTIVITIES

Zero Emission Coal Alliance (ZECA)

This novel zero-emission coal concept was originally proposed by the Los Alamos National Laboratory in New Mexico, U.S. The concept is now being pursued by a U.S.- Canadian consortium, known as ZECA, the *Zero Emission Coal Alliance*. Currently, ZECA has underway a US$550,000 techno-economic feasibility study of the proposed technology, to be completed by early 2001. Membership in ZECA includes eight U.S. coal producers, utilities and manufacturers and the Los Alamos National Laboratory. Members of the Canadian group are: EPCOR, SaskPower, Ontario Power Generation, TransAlta, AFL Venture (ATCO, Fording Coal and Luscar Ltd.), the Coal Association of Canada, and the governments of Canada and Alberta. Each of the participants is contributing US$50,000 to the cost of the feasibility study.

The heart of the concept is the anaerobic gasification of coal, which produces hydrogen and CO_2. No combustion takes place. The hydrogen is then used as fuel in a high-temperature solid-oxide fuel cell to produce electricity. The CO_2 is removed from the vessel by reacting it with lime, CaO, to form a mineral, calcium carbonate ($CaCO_3$). The $CaCO_3$ is subsequently calcined at high temperatures, releasing a pure stream of CO_2 and CaO, which is then is recycled.

The released CO_2 is reacted with naturally-occurring serpentine, a magnesium silicate. The product of the reaction is magnesium carbonate, a benign mineral which could be stored at the serpentine mine. Figure 6 shows the above steps in a pictorial schematic.

BP Amoco Joint Industry Project (JIP)

Six global energy companies have joined with BP Amoco to develop advanced CO_2 separation and geological storage technology. BP Amoco's partners are Chevron, Norsk Hydro, Statoil, Shell, Suncor Energy (Canadian) and Texaco. While each member company is actively working to manage its own GHG emissions through a portfolio of initiatives, this project demonstrates their joint commitment to address the climate change issue through advanced CO_2 capture and storage.

Some of the capture research BP Amoco is planning may be carried out at the International Test Centre at the University of Regina. It is also possible that Canadian O_2/CO_2 combustion technology could play a role in this project. BP Amoco itself is considering a major natural gas decarbonization project for the Alaska North Slope in, which CO_2 would be removed from gas turbine exhausts and used for enhanced oil recovery.

6. A PATH FORWARD FOR CANADA

The Canadian projects listed above comprise relatively modest pilot-scale developments as well as reservoir characterization and monitoring studies. These projects are important and useful in providing new knowledge for the next stages in technology development. They also have a high profile on the international stage. However, if CO_2 capture and storage is to make the significant contribution to GHG mitigation in Canada that is envisaged possible, a much more ambitious program approach is required.

Next Steps

- Canada's First National Business Plan on Climate Change, developed by federal and provincial governments for meeting the Kyoto target, will be in place next year. It announces the creation of an inventory of stationary sources, and storage capacities and characteristics of EOR reservoirs, deep coal seams and saline aquifers. It also outlines support for the further development of capture and storage technologies and their deployment, beginning with CO_2-based EOR.

- Plans for an eventual demonstration of capture and storage of CO_2 are at an early stage, but are expected to lead to demonstration projects by key industries likely to be affected, such as coal-fired electricity and oil sands producers. The recently-announced Canadian Clean Power Coalition is moving forward aggressively and intends to develop a retrofit technology which will allow currently operating plants to reduce all emissions, including CO_2, to target levels within 7-8 years.

- Following the completion of its techno-economic feasibility study in February 2001, the Zero Emission Coal Alliance will decide whether to push ahead and build a ZECA pilot within five years.

- The National CO_2 Capture and Sequestration Initiative will continue its supporting role. A very important product will be expansion of the technology pages and Gantt charts to a much more comprehensive and realistic level (see also the Appendix).

7. CONCLUSIONS

- The use of capture and storage is likely to play a critical role in the world over the next 25 years as it will allow the existing fossil fuel-based energy infrastructure to continue in a environmentally friendly fashion, while providing time for the development of new, lower carbon-intensive technologies.

- Capture and geological storage represent a highly attractive option for Canada to reduce its GHG emissions and move closer to meeting its Kyoto target obligations. Modelling studies indicate that this technology could ultimately account for 20% of the emission reductions required to bridge the gap between Canada's Kyoto target and the predicted business-as-usual emissions.

- Various pilot-scale projects as well as reservoir characterization and monitoring studies are in progress in Canada; several feature international collaboration. While most are of modest nature, they have a high profile on the international stage and brought the recognition that Canada is one of the leading forces in this field.

- Canadian federal and provincial governments have recognized the urgent need to develop capture and storage technology. The First National Business Plan on Climate Change outlines support for the technology and identifies specific action plans.

- Canadian coal and electricity producers have formed a coalition to secure a future for coal by addressing all air emissions of concern. They are developing a 10-year, C$1 billion program to build a retrofit capture demo plant by 2007, and a new, low-emission coal-fired power plant by 2010.

- The National Capture and Storage Initiative is playing a coordinating role, with the objective that this technology be available within ten years. Through the Initiative, technology options are being explored, research goals identified and deployment issues addressed.

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APPENDIX

A number of capture and storage technology options has been identified by the National Initiative on CO_2 Capture and Storage in during a series of workshops during 1998-1999. Each option is described by a technology page in the Proceedings, as well as by a schedule or Gantt Chart. The following technologies were chosen as “significant” for Canada.

Technology options for capture of CO_2:

- chemical (amine) absorption, coal and natural gas plants
- decarbonization of fossil fuels (methane, solid fuels)
- O_2/CO_2 combustion
- as CO_2 hydrates from flue gases
- membrane and cryogenic separation
- anaerobic (zero emission) coal gasification

Critical steps in the technology, especially CO_2 capture from dilute exhaust gas streams, need to be demonstrated on a large scale and costs are generally high at the current stage of technology development. If capture costs can be reduced to about $20 per tonne from the current level of anywhere between $35 and $50 or higher, there is significant potential for wide deployment of the technology in Canada.

Technology options for geological use and storage of CO_2
(including resource characterization and inventory):

- enhanced oil recovery
- enhanced coal bed methane
- deep saline aquifers
- mineral trapping / surface sequestration
- resource characterization and inventory.

Science and technology (S&T) needs and approximate timetables to the first commercial plant were mapped out by the Committee and are summarized in Table 1 below. Early estimates of costs for development and, in some cases, pilot and demonstration plants are included in the Table. Further refining of these figures is needed. However, even though not all options would ultimately go forward, it can be assumed that overall development of these technology options would cost in the hundreds of million dollars and, as previously noted, large demonstration and first commercial plants would cost well in excess of this figure, probably close to a billion dollars.

Table 1: Preliminary Canadian S&T needs for the further development, demonstration and deployment of CO_2 capture and separation technologies

TECHNOLOGY	DEVELOPMENT TIMELINE SUMMARY 2000 2005 2010 2015 2020	ESTIMATED OVERALL COSTS (millions)
CAPTURE		
Absorption (coal and natural gas)	Int'l Test Centre – Coal Demo – Natural Gas Demo	40
Decarbonization of methane	Development – Demo	38
Decarbonization of solid fuels	Systems and Design Studies – Natural Gas Demo	200
O_2 / CO_2 Combustion	Pilot Scale – Demo – Commercial	110
CO_2 Hydrates	R&D and Pilot – Demo	63
Membrane and Cryogenic Separation	R&D – Pilot Units	10
Anaerobic (zero emission) coal gasification	R&D and Pilot – Demo	100-500
STORAGE		
Enhanced oil recovery	CO_2 Monitoring (Weyburn) – More Field Projects	100
Enhanced coal bed methane	Reservoir Assessment – Demo	25
Deep saline aquifers	Identify Formations	0.25
Mineral trapping	(Associated work anaerobic coal gasification)	0.20
Resource characterization and inventory	Reservoir Characterization	15.5

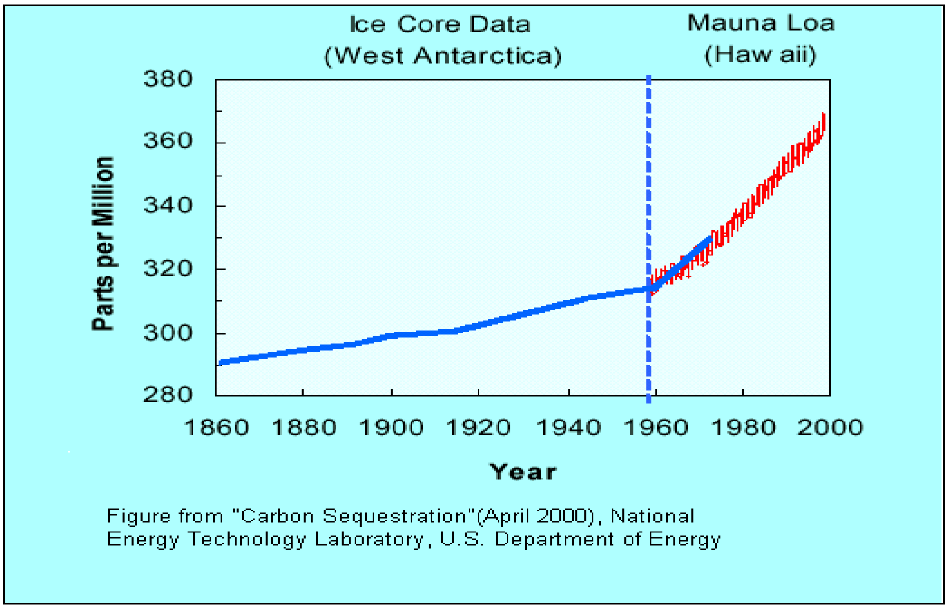

Figure 1. Atmospheric CO_2 concentration

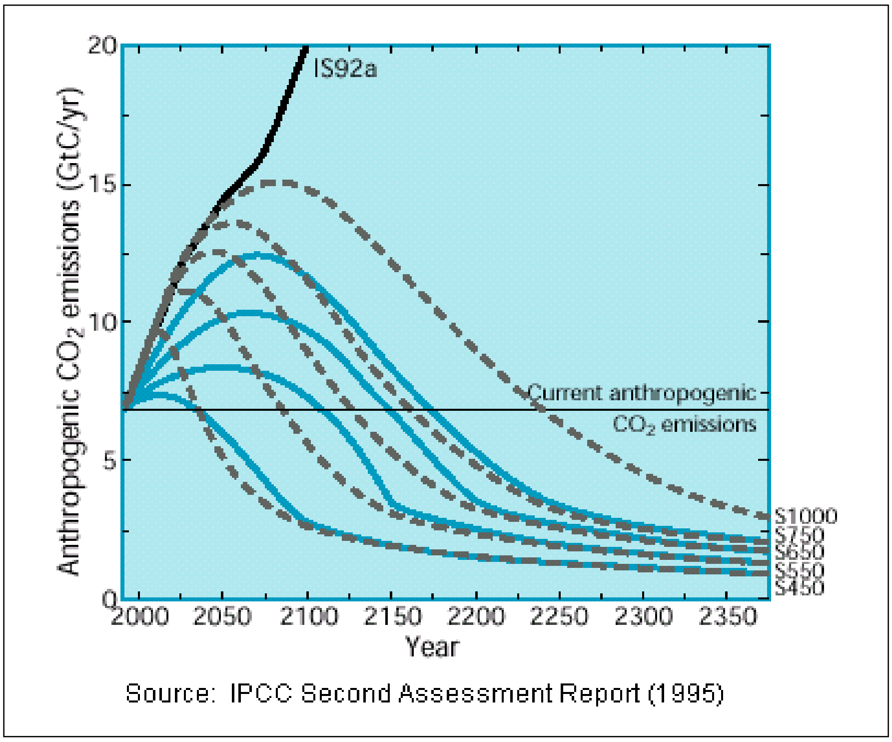

Figure 2. Annual emission levels to achieve CO_2 stabilization

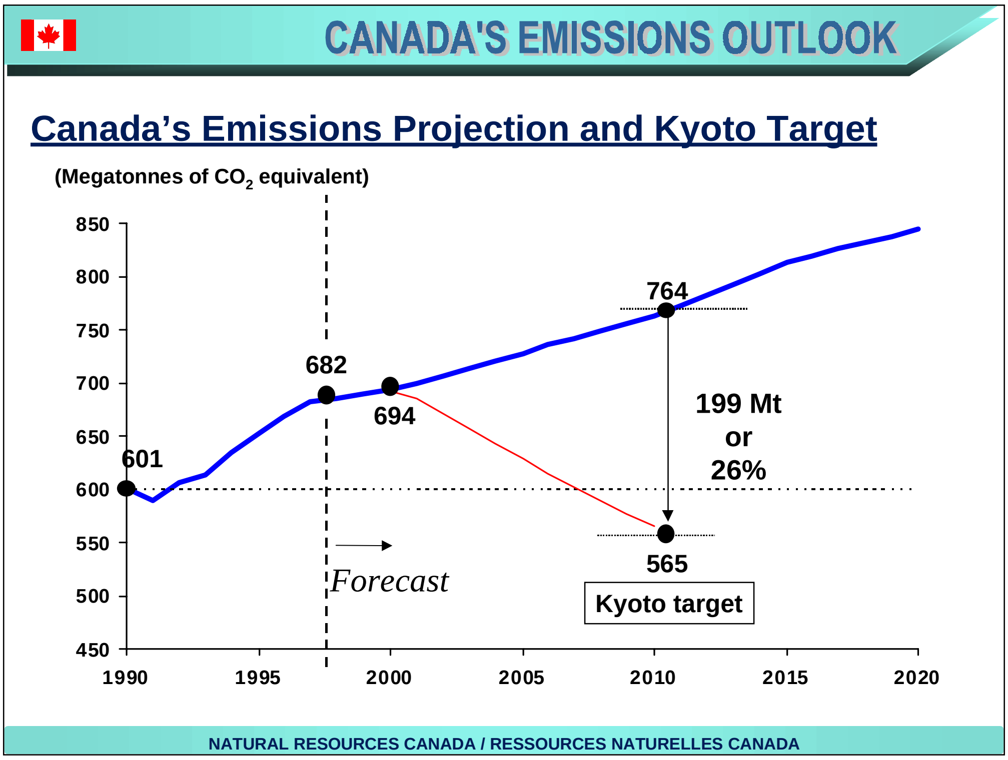

Figure 3. Gap between Canada's BAU projection and Kyoto target

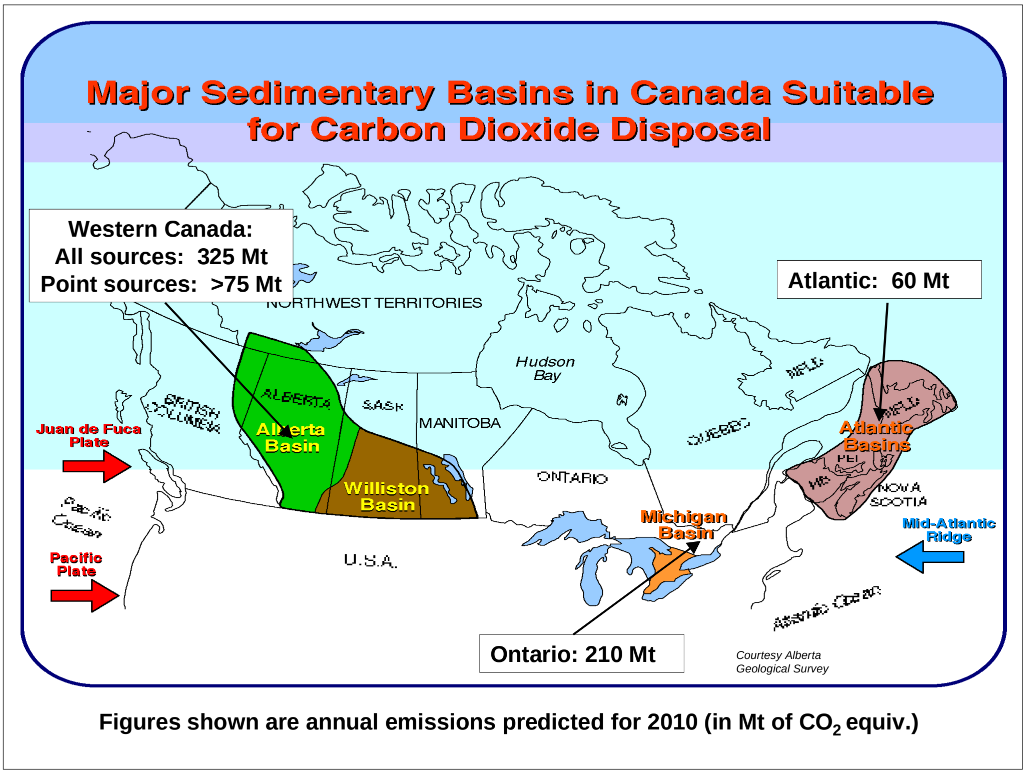

Figure 4. Major CO_2 sources and geological reservoirs for disposal

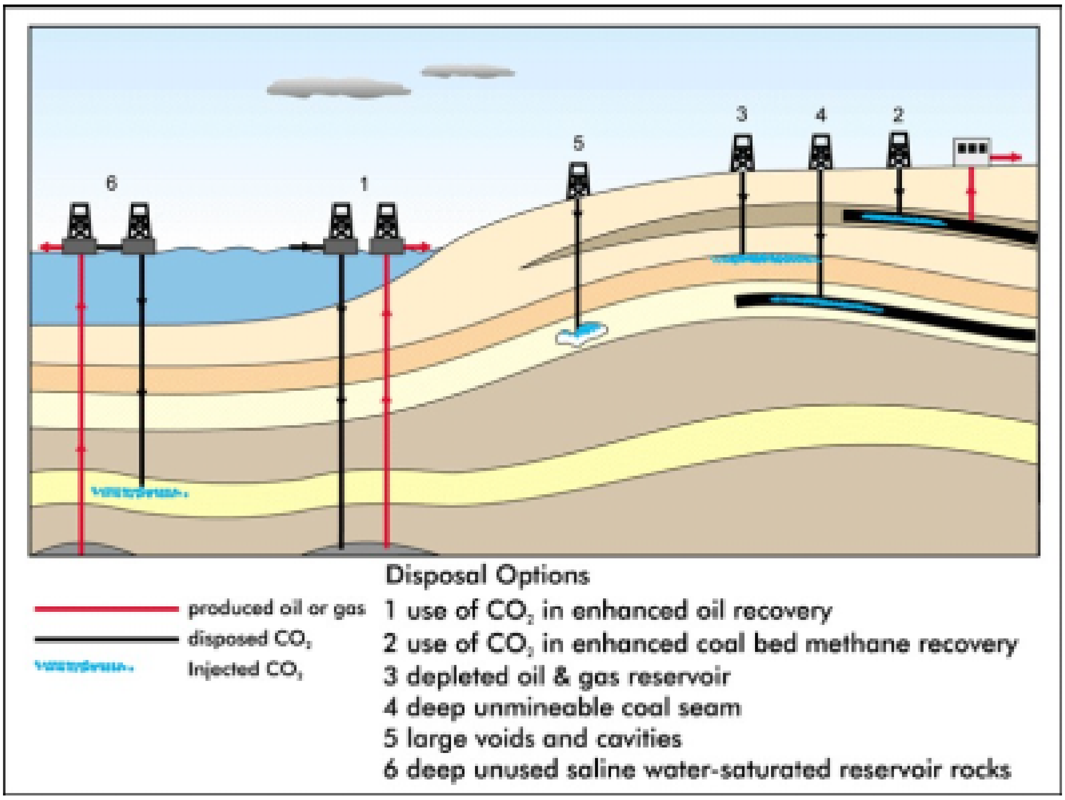

Figure 5. Various geological storage options for CO_2 (courtesy: CSIRO, Australia)

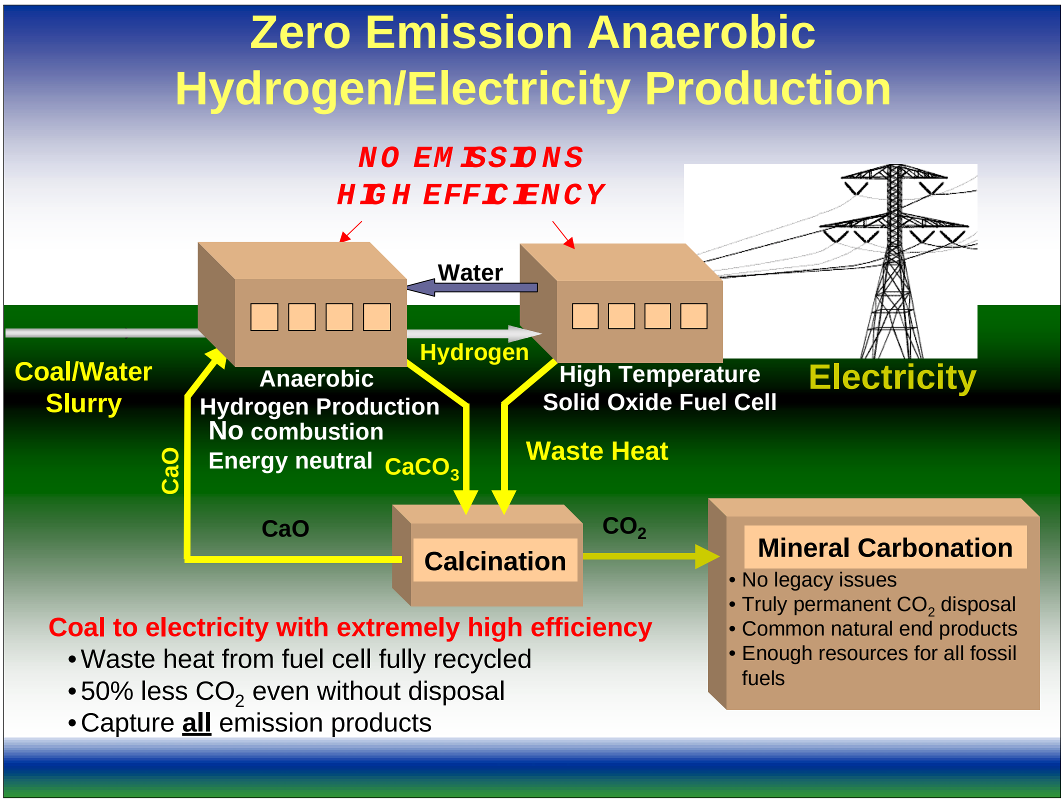

Figure 6. Pictorial schematic of ZECA concept